OXER & FRENCH

Attenuation in Alternating Current Transmission Lines

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Attenuation In Alternating Current Transmission Lines

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

MAURICE DEEN FRENCH and GEORGE CARL OXER

ENTITLED ATTENUATION IN ALTERNATING CURRENT TRANSMISSION LINES

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE

OF Bachelor of Science in Electrical Engineering.

Morgan Brooks

HEAD OF DEPARTMENT OF Electrical Engineering.

1903

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INTRODUCTION.

It is a well established fact that attenuation plays an important part in the operation of long telephone lines, where very small currents and high frequencies of 400 to 700 are used. In fact this factor is of such great importance that unless means are employed to reduce it, successful telephony is limited to a comparatively short distance.

However nothing is known about the part attenuation plays in the transmission of electrical energy over long distance transmission lines, and it the object of this work to investigate to what extent, if any, it does enter into the problem, at frequencies of from 25 to 60.

THEORETICAL.

It has been within the last twenty years that much has been accomplished in the study of the propogation of electrical waves and the measurement of their length. Aboutthis time Hertz discovered a method of producing waves, the length of which could be measured in the laboratory. This method however applied only to very short waves, the oscillations producing such waves having a frequency of something like one thousand million per second.

But in practical cases where the oscillations reach perhaps a few hundred per second at most the waves produced by these relatively slow vibrations are hundreds of miles long. Up to the last four years nothing had been done which would throw any light upon the mathematical theory of these long electrical wave It was in this year that Dr. M.I.Pupin, in a paper before the American Institute of Electrical Engineers, set forth a mathematical theory completely covering this point.

These long waves are produced by forced oscillations, as distinguished from free oscillations, and usually proceed from a generating apparatus of large impedance and are transmitteda distance for the purpose of being absorbed by a receiving apparatus of large impedance.

The principal question involved then in the mathematical theory of waves is :- How much of the energy which is generated reaches the receiving end. This was shown by Dr. Pupin.

An electrical wave may be defined as the periodic distribution over a line of the energy which at any moment is stored up in the medium surrounding the line.

Electrical wave transmission consists in transmitting electrical energy over a conductor where the distance between generating and receiving end is great enough to permit an electrical wave, or a large portion of a wave to be developed. This is the case if we have a very long transmission line, but here the reactions of the receiving end are the essential reactions which the generator has to overcome, and are great in comparison with those og the transmission line.

The case of the piston rod of a steam engine serves as a good analogy. Here the reactions set up in the piston rod itself are small compared with the motor reactions and the driving pressure. But if we consider the piston rod as very long, we can no longer think of the piston rod as a perfectly rigid connection between the transmitting and receiving end. Consequently energy will will not be delivered at the receiving end at the same rate as at the generating end at any moment, because of a lag in phase. The energy which is to be transmitted is first stored in the piston rad, and then delivered to the motor. While thus stored it exists partly as kinetic energy of the moving mass of the rod and partly as potential energy due to the rods elastic deformation.

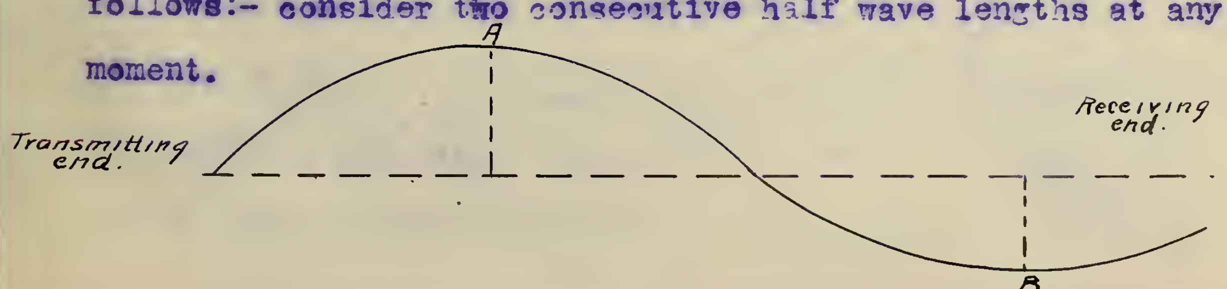
The process of transmission consists in successive transformation of the kinetic into potential energy and vice versa. These transformations being progressive the energy is propogated along the rod and we say that the propogation is a wave propogation, in order to express breifly the fact that progressive motion along the rod is a periodic one.

Just these same conditions exist when electrical energy is

transmitted by a periodically varying Electro Motive Force acting on a long conductor. While the energy is stored up in the medium it exists there partly as magnetic flux and partly as electrical flux. The process of propogation consists in the transformation of the magnetic into the electrical energy and vice versa. When the impressed Electro Motive Force is a periodic one the propagation will be in the form of electrical waves.

At points of maximum electrical energy the potential is a maximum and at points of maximum magnetic energy the current is a maximum. Then considering the distance between any two consecutive points of maximum current or maximum potential we have this as one half a wave length. This wave length may be anything from a few inches to hundreds of miles long depending upon the velocity of propagation. In this wave transmission of energy from one point to another, part of it is dissipated due to the imperfect conductivity of the transmission line. If the conductivity were perfect all of the energy would be delivered. This dissipation is due to the resistance of the conductor, although capacity and inductance may seem to dissipate energy, they do not, but regulate that due to the resistance. For in fact inductance and capacity effects are the storing up of energy in the surrounding medium.

To this loss of energy may be said to be due the attenuation of the wave during its transmission, and is expalained as follows:- consider two consecutive half wave lengths at any moment.



Call the one nearest the transmitting end, a , and the next consecutive one, b. Then the wave energy stored up in, a, is greater than that in, b, because of the loss due to imperfect conductivity. Hence the wave energy in a long transmission line is gradually dissipated during its propogation and so the amplitude of both current and potential gets smaller as the energy progresses. The effect of attenuation is expressed mathematically in an equation, involving the attenuation constant. Let , K, be the amplitude of current at transmitting end and K', be the amplitude at distance , s, from transmitting end, and if the whole line be infinitely long, the expression $\frac{K'}{K} = \varepsilon^{-\beta s}$, where , e, is the base of Naperian logarithm system, and , β, is the attenuation constant. The value of, β, is given in terms of resistance, inductance, capacity and frequency and is

$$\beta = \sqrt{\tfrac{1}{2} p C \left[\sqrt{p^2 L^2 + R^2} - p L \right]}$$

It has been shown that inductance and capacity regulates the dissipation and the introduction of high inductance decreases this dissipation.

Taking the expression for, β, and suppose that we make, L, very large compared with, R, so large that in fact , R, will be but a small percent of, L. Then the expression will reduce to,

$$\beta = \frac{R}{2}\sqrt{\frac{C}{L}}$$

For in extracting the square root of the sum of squares of two numbers in which, a, is much greater than, b, as $\sqrt{a^2 + b^2}$ we may write it immediately as $= a + \frac{b^2}{2a}$

Then $$\beta = \sqrt{\tfrac{1}{2} p C \left[\left(pL + \frac{R^2}{2pL} \right) - pL \right]}$$

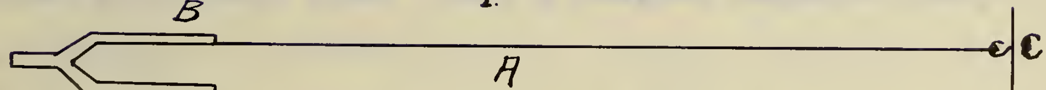
$$= \sqrt{\tfrac{1}{2} p C \cdot \frac{R^2}{2pL}}$$

$$= \sqrt{\frac{R^2}{4} \cdot \frac{C}{L}} = \frac{R}{2}\sqrt{\frac{C}{L}}$$

which shows that in this case, B, is independent of the frequency, due to the high inductance and if, L, is very large, as supposed, B, becomes very small. Also if, c, is much greater than, L, and still, L, much greater than, R, we see that, B, becomes large, which shows that a large capacity helps to cause the dissipation of energy, as shown in the case of a long cable. This propertyof inductance is now used to advantage in long distance telephony in Germany, wherea line has been equipped with induction coils.

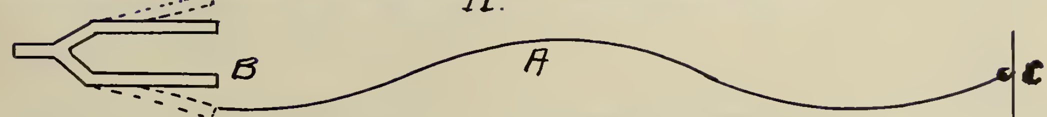
In order to illustrate more plainly the effect of attenuation and the introduction of inductance coils, the case of a cord fixed at one end and attached to a tuning fork at the other is an exact analogy of electrical propogation of waves and the accompanying dissipation.

I.

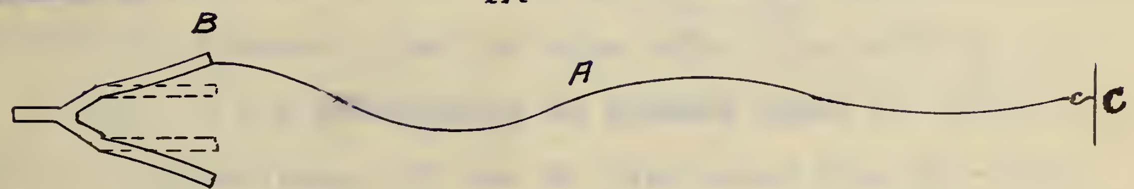


Consider a cord as shown in, A, attached to a tuning fork, B. If the prong of the fork is made to vibrate a series of waves will be propagated along, A, as shown in <u>11</u>

II.

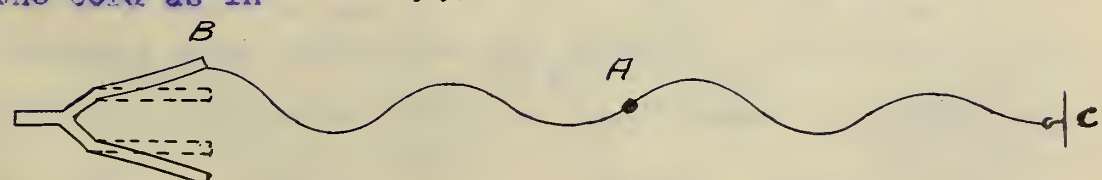


If the frictional resistances opposing the motion of the cord be very small and the cord long enough to have several wave lengths, the reflected waves coming from the fixed end,c, will be approximately the same amplitude as the direct wave from the tuning ~~wheel~~ fork. If, however, the frictional resistances are not small, then there will be dissipation of energy as the wave progresses and the reflected wave will have a smaller amplitude than the direct wave and consequently an interference will result. This result is attenuative and produces an effect as shown in III



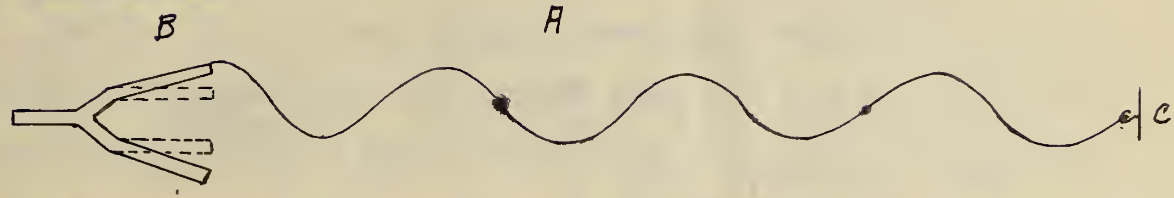
If the cord in this case is very light the attenuation will by very great and if the mass of the cord is increased, the attenuation decreases, for the reson that a larger mass requires a smaller velocity in order to store up a given quanity of kinetic energyand a smaller velocity brings with it a smaller frictional loss. Also a smaller velocity means a shorte wave length.

To show the effect of placing a large inductance in a single place in a line, suppose we concentrat a weight in the middle of the cord as in IV.



The mass, a, then begins to be a source of reflection the same

as, c, less wave energy reaches, c, than before. But if this mass is sub-divided into two pieces and placed equi-distant on the cord as in V



The reflex action will not be so great thus increasing the efficiency of transmission and so on if this mass is still sub-divided and distributed along the cord, it becomes nearly the same as a single cord of the same mass, and of uniform density, and it vibrates nearly like the same under like conditions.

A limit to the sub-divsion is reached when, no further benefit is appreciable. It was by this means that Dr. Pupin proposed to increase the efficiency of transmission of electrical waves. For small inductances inserted at proper intervals do for a transmission line what the weights do for a cord.

The length of a wave can be computed by means of the formula $\lambda = \frac{2\pi}{p\sqrt{2LC}}$ where λ = wave lengths in miles, L, the inductance, c, the capacity and, p, the frequency speed or $\lambda = \frac{1}{f\sqrt{2LC}}$ where f is the number of alterations. From this we see that the length of the wave depends upon the frequency, say 600 to 700 as in telephone work, the wave length will be comparatively short.

But maintaining a constant frequency, the wave length then depends upon inductance and capacity of the line. The velocity of propogation of waves also depends upon these quanities, for $\lambda = \frac{1}{f\sqrt{2CL}} = \frac{1}{f} \cdot V$ where V is the velocity of propogation. $\lambda = \frac{V}{f}$ $V = \frac{1}{\sqrt{2LC}}$ $V = f\lambda$.

That is, keeping the same line constants, the velocity of propogation will be the same for all frequencies, but the wave length will vary.

If the line is very long a great many waves will be propogated in transmitting the energy from one end to the other, hence we will have a large percent of the energy dissipated.

In the case of high tension transmission lines we have a much different condition of affair. For here the frequency varies from ~~twenty five to 133~~ 25 to 133 alternations per second, thus giving a very long wave and unless the transmission line itself is very long but few waves or possibly a fraction of a wave will be propogated and hence very little loss due to the attenuation of the wave.

It is generally conceeded that the current density is equal at all points of a uniform transmission line, but if a number of waves are propogated there will be attenuation of the wave, which decreased the amplitude of the wave, hence a dissipation of energy. It necessarily follows that the current will be smaller at the receiving end , although this loss may not be a large percent of the total current transmitted.

It is the purpose of this work to derive a means of measuring this difference in value of the current at different points along a transmission line. For this purpose an artificai line had to be constructed an account of which will be given later.

For the measurement of the difference in the value of the current, the best scheme which suggected itself was to measure the difference in the magnetic flux created about the conductor. In two inductive coils of equal turns, and having the same

value of current flowing through them, the flux, or Maxwell's surroundings each coil will be identically the same. But if one coil has a greater current than the other then the flux around this coil will be greater and if the current at any instant is flowing in opposite directions in the two coils, the resultant flux will be the difference. That is, if in coil, A, the flux $\phi = \frac{4\pi}{10} NI$; and the flux in coil , B, $= \phi' = \frac{4\pi}{10} NI'$; or the resultant flux $\phi'' = (\phi - \phi')$ $= \frac{4\pi}{10}(I-I')N$. It follows then that if these two coils are surrounded by a third coil, the resultant flux ϕ'' will ~~xx~~ induce in this coil an Electro Motive Force which produces a current that can be measued by putting a galvanometer in the circuit, or merely detected by inserting a telephone receiver. The object then was to insert one of these coils in the line at the receiving end and another at any other point along the line and if there is a difference in the value of the current, the resultant flux ϕ'' is produced and the current producing it is measured by the galvameter.

EXPERIMENTAL.

In the experimental work first planned we attempted to construct an artificial cable with the same line constants as an ordinary transmission line as far as resistance and capacity were concerned but the inductance was to be supplied as an auxillary. In making this piece of experimental work tin foil strips 2 1/2 inches wide were laid continuously on paraffined paper. These strips were placed 1 inch apart and when one sheet was covered another sheet was laid on this one and the strip of foil then was wound on this sheet in an opposite direction to that on the first sheet. Thus, when made up, the whole arrangement was non-inductive.

Considerable difficulty was experienced at first in various ways. Extreme care had to be used in selecting and preparing the paper so as to avoid any perforations or bad spots in the paper also being careful to entirely cover the paper with paraffine. This latter was finally overcome by placing two rollers on the side of the reservoir, in which the paraffine was heated, carefully immersing the paper in the paraffine and then running it between these rollers; thus taking off the surplus paraffine and at the same time, forcing it thoroughly into the paper.

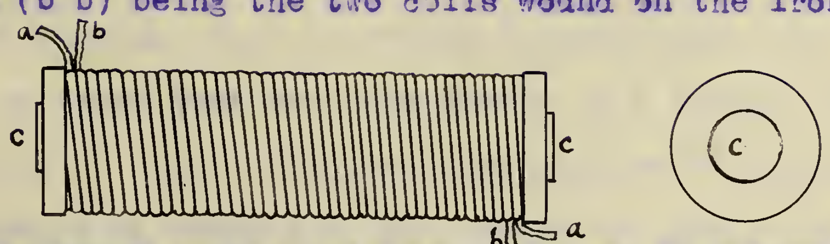
The strips of foil were very difficult to handle and great care had to be taken in the winding, spacing and lapping, especially on the corners and turns. Good electrical connection was difficult to make , but by using copper plates and clamping the foil between these fairly good connections were obtained

After making nine sheets, as described above, size 18" x 24 we made several tests. We clamped these sheets in a frame and found that the resistance varied with the pressure exerted upon the clamps, although not to any great extent at the same time was very annoying. We rewound the sheets, giving special care to the joints and turning points, but still found the same trouble.

In testing for capacity we found an infinite amount and, after much more experimenting with the same results , we abandond this plan.

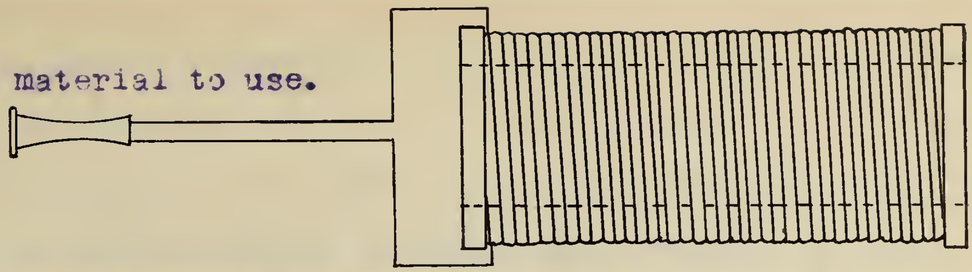
The rest of the expermenting was done by using inductance coils for inductance and resistance, also non-inductive coils for resistance, and condensers for capacity. With these we obtained our line constants.

For detecting any attenuation or difference of phase a telephone balance coil was made and used. This consists of two separate coils wound on the same iron core and so connected to the line that the current flows through the coils in opposite directions, these coils being connected at different points in the line. Figure 1 shows the construction of this coil. (a a) and (b b) being the two coils wound on the iron core (c c)



Another spool containing many turns of fine wire was wound into which the above spool would slip. Figure 2 shows this second or telephone spool. The ends of this fine wire were connected to a telephone receiver . This spool was made of pasteboard, paper, glass and wood. This last was finally decided upon

as the best material to use.



The principle upon which this apparatus works is a magnetic one. The lines of force generated in the two coils in figure 1 would exactly oppose each other if there was no attenuation nor phase displacement, considering the coils wound exactly as described. If the lines of force exactly oppose one another no lines would cut the fine wire coil, hence would produce no sound in the telephone receiver, but if these lines did not balance there would be an audible sound in the telephone.

The main difficulty encountered in this apparatus was in the making of the opposing or balancing coil. Many attempts were made in winding this coil and several different methods used. We took two double cotton covered copper wires, about #9, and wound them side by side, with equal tension on the iron core, about twenty five turns was given each wire. Testing this we found it badly out of balance and, attempting to balance it, we could get on either side of the neutral joint but it was too sensitive to exactly catch this joint. Merely increasing the pressure or tension would throw the balance badly off.

Next we wound just one wire giving it a certain number of of turns, and on top of this we wound another wire of the same size and giving it about the same number of turns. We hoped to be able to adjust this outer coil and not disturb the inner, an advantage over the first method where both coils had to be adjusted simultaneously.

This second method seemed to give better results and we

obtained a much closer balance. When we had the balance as near as possible if we changed the current the balance was badly off and the readjustment of the outer coil was necessary. The lines of force from the inner coil had to be greater in order to balance the lines from the outer coil, for we had a few more turns in the inner coil than in the outer coil when the balance was as near obtained as possible. When the current was changed there had to be a change in the number of turns before anything like a balance was obtained. Although a more nearly perfect balance was obtained by this method, it had to be discarded on account of the unbalancing effect produced by a change in the current.

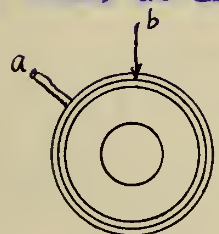
Next we returned to our original idea of winding two wires side by side. After many failures we finally made a coil that was balanced perfectly. We covered the whole inner coil with paraffine thus holding the turns in place. With this coil we obtained the best results of any coil experimented upon up to this time. The large capacity that we were using was discharged accidentally through this coil and either this or too great a current caused a short circuit in the coil and destroyed it.

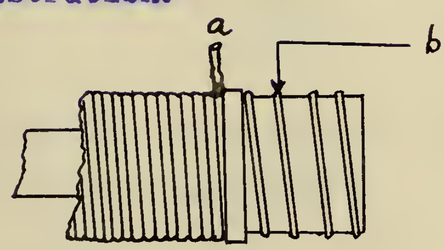
As the method of winding the two coils together seemed to be the one best adapted for our work we wound our next coil with twin office wire. The first one wound up was found to be perfectly balanced. This twin wire was a great improvement over winding the two coils from separate wires not only in having accurately equal number of turns in each coil but its insulation was very much better. With this coil we obtained the conclus-

ions that follow.

After using this coil for some time, (and always and before and after each test we saw that it was balanced) it became unbalanced for some unkown reason; hence, although in theory these coils are easily made, in practice they are not only extremely difficult to wind but after winding, they very easily get out of balance and are also extremely sensitive.

If, however one end of each coil is brought out in such a manner that a sliding contact can be made, the balance can be maintained perfectly by simply altering the number of turns on either coil, as shown in illustration.





The altering of the number of turns can be done to a small fraction of a turn by simply sliding the contact, c, around the circumference in the same manner as a cylinder bridge.

With such a set of coils as previously described we proceed to investigate several built up lines in the following manner:-

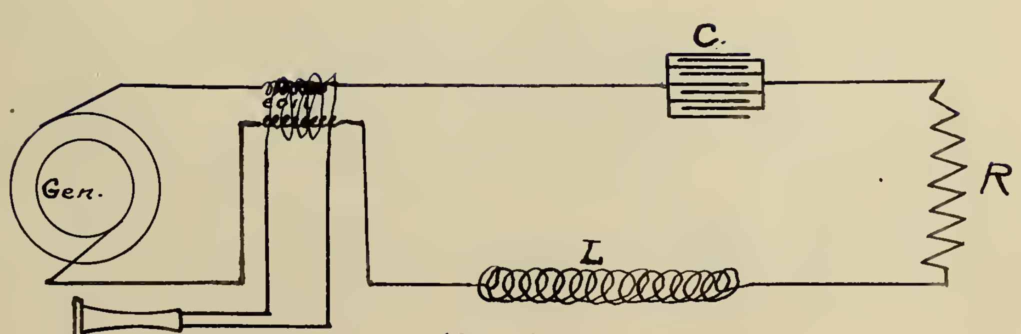
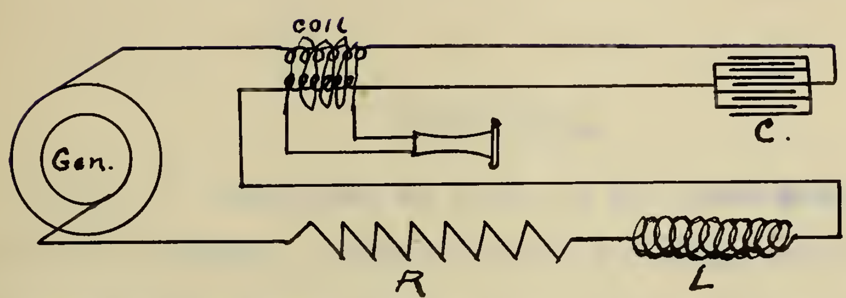


Fig-1

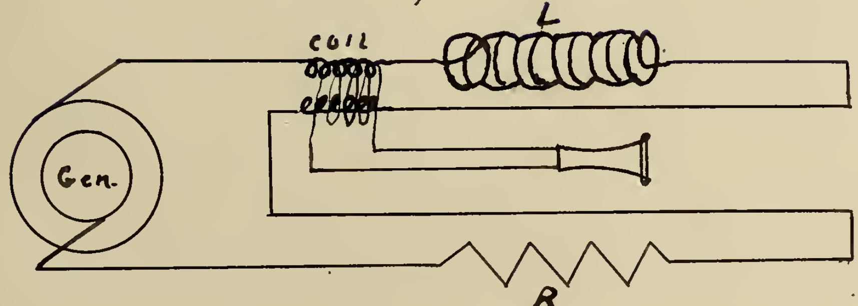
In figure 1 a circuit was made up by putting a large Capacity, Resistance and Inductance in series with 60 cycle 110 volt generator. The two induction coils were then put in a circuit, with all the Resistance, Inductance and Capacity between the coils. No sound was perceptable in the telephone with this arrangement, due probably to the balancing effect of the Inductance and Capacity. No further tests were made this arrangement.

Fig-2-



In figure 2 the same Resistance, Capacity and Inductance was used on a 110 volt 60 cycle circuit with the coils in the circuit, having the capacity between them. A very faint sound could be heard in the telephone occassionally, but was not sufficient to warrant any conclusion to be drawn.

Fig-3



There seemed to be a balancing effect where high Inductances and Capacities were used in the same circuit. So a circuit was made up as shown in Figure 3 with a high Inductance between the two coils on one side and a high Resistance and the generator on the other side. With this generator a frequency of form 60 to 110 could be obtained. At the higher frequencies a perfectly audible sound could be had and as the frequency was diminished until at 60 frequencies nothing could be heard.

CONCLUSION.

With the apparatus at hand in the laboratory it was impossible to obtain a line wave at a frequency of over 110, hence on investigation were limited to comparatively low frequencies.

While there was a slight indication of attenuative effects at the higher frequencies used, there was sufficient evidence to warrant the conclusion, that in ordinary frequencies as used in practice, attenuation is such an insignificant factor that it may be entirely neglected.